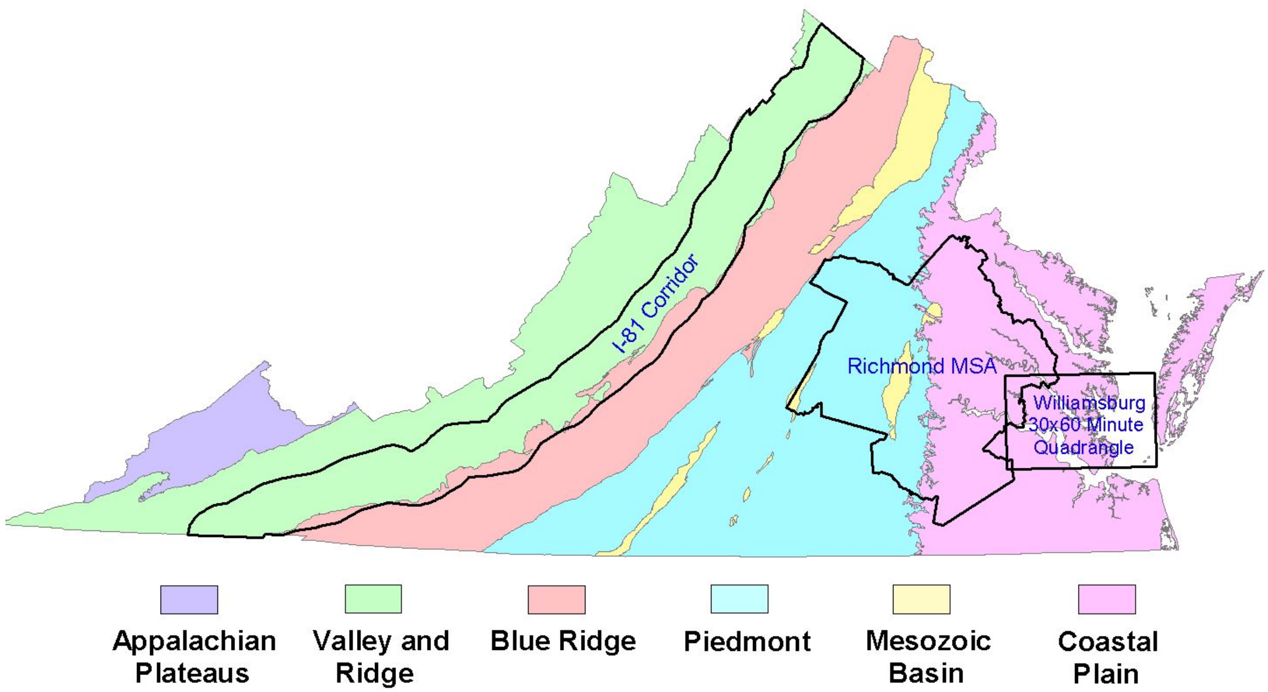
STATEMAP PROPOSAL - VIRGINIA

Submitted in response to USGS Program announcement
No. 08HQPA0003



Virginia Department of Mines Minerals and Energy

October 30, 2007

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INTRODUCTION

The Virginia Department of Mines, Minerals and Energy, Division of Mineral Resources (DMR) seeks continued funding for geologic mapping along the Interstate 81 corridor, in the Richmond Metropolitan Statistical Area, and in the Williamsburg 30- x 60-minute quadrangle. These long-term projects focus our efforts on three regions of Virginia that are in great need of new and accessible geologic information. The maps we produce will enhance Virginia's ability to develop and conserve natural resources in a safe and environmentally sound manner to support a more productive economy.

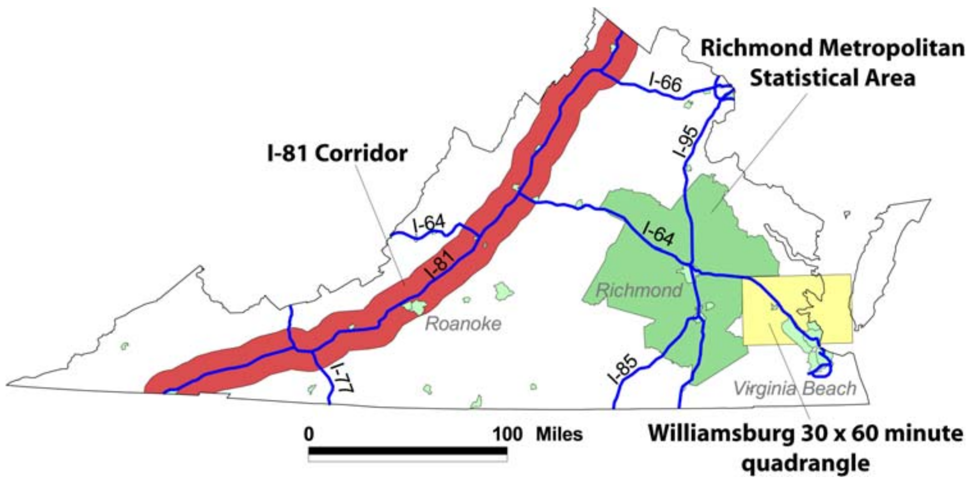

Figure 1. Locations of proposed project areas.

Long Range Plan

On October 3, 2003, DMR's Geologic Mapping Advisory Committee (GMAC) agreed that geologic mapping is needed in Virginia to locate water resources, develop economic products such as aggregate and sand, identify geologic hazards, protect natural resources, site waste disposal facilities, and develop roads and other infrastructure. The GMAC and DMR staff evaluated areas in Virginia with respect to these needs. At the end of this process, three areas where mapping would provide the greatest benefit were identified: western Virginia, particularly along the I-81 corridor; the Richmond metropolitan area; and along the I-64 corridor between Richmond and Virginia Beach. A long-term mapping strategy has been developed for each area. These strategies consider regional needs, development patterns, mineral resources, the location of existing mapping and staff resources.

DMR recognizes that STATEMAP funding is vital to the completion of long-term mapping projects. We have taken several steps to increase the efficiency of our mapping program and make the very best use of available funds. A significant action has been to schedule the completion of quadrangles in the I-81 Corridor project to take advantage of recently "retired" geologists who have experience in the project areas. These geologists begin work with knowledge of the local stratigraphy and in some cases, existing data. As a result, they are able to complete projects in less time at a reduced cost. The cost per quadrangle contractor projects is approximately 70% of the cost for projects completed by DMR staff. We have also minimized travel-related expenses by dividing work on the

Richmond MSA project between our Charlottesville and Williamsburg offices and basing a second geologist in Williamsburg. A third strategy is to take advantage of existing subsurface data by converting water well records into a searchable database and obtaining copies of drilling logs generated during environmental and geotechnical investigations in the Richmond area from a local engineering company and state transportation and environmental agencies.

Virginia Growth

Virginia is home to more than seven million people. The population of our state is expected to reach almost ten million people by 2030 (U.S. Census Data, 2005). Two thirds of this growth is expected in the Washington D.C., Richmond, and Virginia Beach–Norfolk–Newport News areas (Figure 2). Much of the remaining growth will occur near major highways such as Interstate 81.

Approximately one million people currently live within 10 miles (16.1 km) of I-81 (U.S. Census Data, 2000). Municipal centers in the I-81 corridor include the cities of Winchester, Harrisonburg, Staunton, Lexington, Roanoke, Salem, Wytheville and Bristol. The I-81 corridor's population is expected to grow more than 15 percent by 2030 (Virginia Employment Commission, 2003). Approximately 90 percent of this growth is expected to occur in areas that are currently unincorporated.

Approximately 1.1 million people live in 16 counties designated as the Richmond Metropolitan Statistical Area (U.S. Census Data, 2000). Municipal centers include Richmond, Petersburg, Hopewell, and Colonial Heights. The population of this area is expected to grow approximately 35 percent by 2030 (Virginia Employment Commission, 2003). Almost all of this growth is expected to occur outside of existing city boundaries.

Approximately 470,000 people live in the Williamsburg 30- x 60-minute quadrangle (U.S. Census Data, 2000). Municipal centers include Hampton, Newport News, Poquoson, and Williamsburg. The population of this area is expected to grow approximately 20 percent by 2030 (Virginia Employment Commission, 2003). Much of the growth will occur outside existing city boundaries.

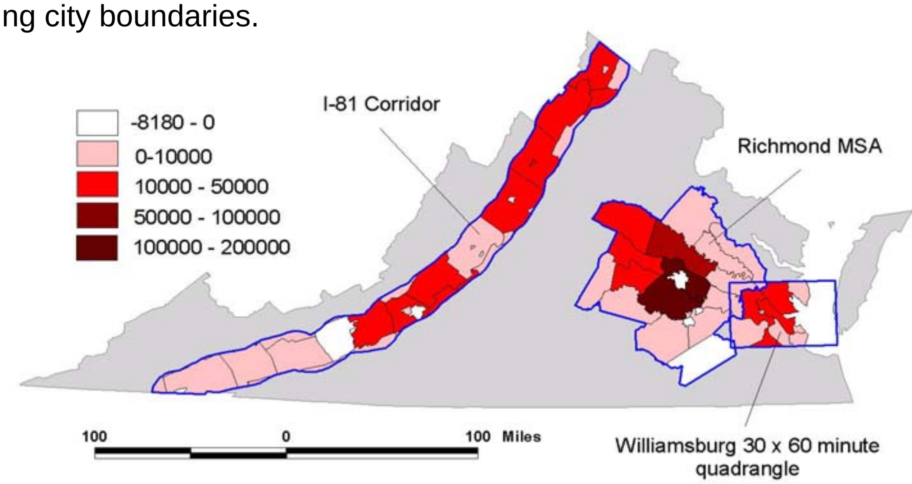

Figure 2. Projected population change, by county and municipality, in proposed project areas from 2000 to 2030 (Virginia Employment Commission, 2003).

INTERSTATE 81 CORRIDOR PROJECT

Introduction

DMR proposes to continue a concentrated multi-year effort to complete 1:24,000-scale geologic mapping and digital compilation of existing geologic maps along the entire I-81 corridor in Virginia. This portion of the Appalachian Valley is where most of the population lives, works, and travels on a daily basis. It is home to a variety of farms, industries, and commercial enterprises. I-81 is also a nationally significant transportation corridor that connects manufacturers and markets from the southern and northeastern United States.

For the purpose of this study, the I-81 corridor is defined to extend for 10 miles (16.1 km) on either side of the highway. DMR plans to complete 1:24,000-scale geologic mapping of all quadrangles that are wholly or substantially within this corridor. DMR also plans to selectively map quadrangles that are adjacent to the I-81 corridor in areas of current or future growth and in areas where detailed geologic mapping is warranted because of structural or stratigraphic complexity.

Intermediate products for this study will be 1:24,000-scale geologic maps of single or multiple quadrangles, to be published in paper or digital form, and a series of open-file reports on CD that contain files for the current extent of the geologic compilation. The final product will be a 1:24,000-scale digital compilation of the entire corridor.

Location and Geologic Setting

I-81 extends for 325 miles in western Virginia, along the Appalachian Valley. It is the longest interstate in Virginia and has 90 interchanges, including intersections with Interstates I-66, I-64, and I-77. Two proposed Interstates, I-73 and I-74, will also intersect with I-81. Since its completion in the 1960's, I-81 has become the "main street" of western Virginia, serving as a corridor for travel, commerce, and development.

Industries and commercial businesses have located in the I-81 corridor to take advantage of the transportation system. Abundant high quality groundwater supplies in some areas have also attracted industries. Away from municipal centers, agriculture is the dominant industry. In 2002, the 12 counties that I-81 passes through contained approximately 11,850 farms on approximately 1.75 million acres (U.S. Department of Agriculture, 2002). This includes nearly 10,000 livestock operations.

The Appalachian Valley contains headwater portions of five major watersheds. Three of these watersheds are located on the eastern side of the eastern continental divide. The Shenandoah-Potomac and James rivers begin in the north and north-central parts of the Valley. Water from these rivers eventually flows into the Chesapeake Bay. The Roanoke River begins in the central Valley and flows into North Carolina where it enters Albemarle Sound and eventually the Atlantic Ocean. The New and Tennessee rivers, in the southern part of the valley, flow northwest and southwest, respectively, and ultimately enter the Mississippi river system.

The I-81 corridor is predominately underlain by clastic and carbonate sedimentary rocks of the Valley and Ridge geologic province. Metamorphic and igneous rocks of the Blue Ridge geologic province underlie a portion of the eastern edge of the corridor.

Early to late Paleozoic-age limestone, dolostone, sandstone, and shale comprise much of the Valley and Ridge province. These rocks formed from sediments that were deposited in a variety of terrestrial and marine settings. Folding and faulting of these rocks, predominantly during the Alleghanian orogeny, has produced complex geologic structures. Subsequent erosion has resulted in a distinctive topography that is dominated by alternating linear ridges and valleys. The stratigraphic sequence in the Valley and Ridge geologic province was first mapped at a scale of 1:250,000 by Butts (1933 and 1940). Subsequent quadrangle, county and 30- x 60-minute quadrangle mapping in portions of the project area have identified additional evidence for faulting and folding and refined the stratigraphy. It is anticipated that the proposed project will continue to identify map-scale structures, harmonize the portrayal of regional tectonic features, and establish a consistent nomenclature in this portion of western Virginia.

Rocks of the Blue Ridge geologic province are Middle to Late Proterozoic and early Paleozoic in age. The older rocks exist as basement and are unconformably overlain by the younger rocks. Both groups of rocks may overlie a major decollement and sit atop rocks that are thought to be correlative to those exposed in the Appalachian Valley. Contacts between Blue Ridge rocks are commonly sheared, making original relationships difficult to determine.

Purpose and Justification

Water resource location, economic product development, geologic hazard identification, natural resource protection and infrastructure development are important issues along the I-81 corridor. Some of these issues are at a critical stage. The need to locate aggregate and identify geologic hazards is very important as Virginia considers capacity improvements for I-81 that includes lane additions and an adjacent long-haul rail system. The need to locate additional water resources continues as development expands. The need to protect natural resources including river systems, forests, groundwater supplies, mineral resources, cave systems, and open space is also increasing in response to development pressures. This project will provide useful information at an appropriate scale to address the issues identified by the GMAC in the following ways:

Water Resource Location

Cities and towns in western Virginia obtain their water supplies from groundwater aquifers, surface reservoirs, or a combination of the two. Away from municipal centers, drilled wells are the primary water sources for residents, businesses, and industry. Well yields vary depending upon rock type, location, and depth. In karst and fractured rock aquifers, well yields are unpredictable. Supplies are typically adequate for residential use, but higher yield supplies for industries and municipalities are more difficult to locate. Some surficial deposits in the Appalachian Valley are significant reservoirs for groundwater. Groundwater residing in alluvial fan deposits supplies many businesses in the Valley, including those that require a high quality water source such as Coors Brewery, Merck Chemical, Hershey's Chocolate, and McKee Foods. Detailed geologic mapping will provide useful information to municipalities, businesses, and industries when siting future wells.

Economic Product Development

The potential for additional aggregate resources exists along the I-81 corridor. The identification of these resources for quarrying will support continued economic development in the region and provide building material for the expansion of I-81 and new structures. High calcium limestones also exist in the corridor. The demand for these rocks is increasing as clean air regulations come into effect. A wide array of mineral resources have been mined in the past along the I-81 corridor, including crushed and dimension stone, metals, clay, and sand. Detailed geologic mapping will provide useful information to mining companies to further develop the region's mineral resources.

Geologic Hazard Identification

Sinkholes are significant hazards along large parts of the I-81 corridor. Between 1971 and 2001, almost 350 sinkholes were discovered in the I-81 right-of-way (Dorman, 2001). In 2001, three successive sinkhole collapses occurred in the median of I-81 within less than a month. Sinkholes are present in other portions of the corridor as well (Hubbard, 1983; Hubbard 1988; Hubbard, 2001). Many sinkhole collapses result from increased water infiltration related to changes in land use.

Landslides/block slides and slope stability are also hazards. These types of problems are common in the northern half of the corridor where the Blue Ridge Mountains meet the Appalachian Valley and in the southern half of the corridor where the hill slopes are steep. Landslides, limited debris flows, and extensive reworking of alluvial boulder deposits can occur during a period of heavy rainfall, like the one experienced with Hurricane Isabel in 2003 and Hurricane Ivan in 2004. Even on moderate slopes, some rock types and geologic structures create stability problems for structures and roads. Areas underlain by shale and some limestone formations are particularly susceptible to erosion, acidity, or foundation shift because of shrinking and swelling of residual clay soil.

Natural Resource Protection

Development pressures within the I-81 corridor are resulting in changes in land use. Open space is being converted to industrial, commercial, and residential use. These changes are certain to have both positive and negative effects on the region's natural resources. In many cases, the geology can play an important role in the nature, type, and extent of these impacts. Detailed geologic maps will provide useful information to land use planners, natural resource caretakers, and environmental consultants who work in the corridor.

Water contamination is a significant problem in many parts of the I-81 corridor. Water quality in the region is impacted by a number of pollution sources, including agricultural run off, failing septic systems, and excessive sedimentation (Virginia Department of Environmental Quality, 2003). Many crops are fertilized with animal waste from concentrated feeding operations such as dairies and poultry farms. Nitrogen loads in the Shenandoah-Potomac basin increased 11 percent between 1985 and 2000, to an estimated total of 12,000,000 pounds (Virginia Department of Environmental Quality, 2003). Nutrients are a major water quality problem in the Chesapeake Bay, which is the ultimate receiver of water from the Shenandoah River (Environmental Protection Agency, 2002). Approximately 52 percent of monitored streams and rivers in the Shenandoah-Potomac basin are threatened, not fully supporting, or not supporting their designated uses (Virginia Department of Environmental Quality, 2003).

Roads and other Infrastructure Development

A statewide expansion of I-81 is in the planning stages and will occur over the next two decades. This expansion project will likely include the widening of the interstate, and possibly the installation of rail along the corridor and other improvements. Additional projects include the construction of I-73 and I-74 in the vicinity of Roanoke. Commercial, industrial, and residential development and associated utilities will likely follow road construction and expansion projects. Detailed geologic maps will provide useful information to the Virginia Department of Transportation, municipal and private utilities, and private and public land developers.

Science Issues

The Valley and Ridge Province in Virginia has been studied for nearly 200 years. It is a classic area of research in the areas of carbonate stratigraphy, invertebrate paleontology, and thin-skinned tectonics. Major research activities include relating lateral and temporal changes in depositional environments to orogenic activity and climate change and unraveling the nature and timing of deformation during the Alleghanian Orogeny. More recent research has focused on the modeling of groundwater flow in faulted and folded clastic-carbonate bedrock terrain, documenting the extent of karst systems and their role in groundwater transport, and understanding the geomorphic evolution of the Shenandoah River Valley. Our mapping program directly supports all of these areas of research by providing basic geologic information and regularly consulting on active projects. In addition, our employees and contractors are regular contributors at GSA and other professional meetings.

Strategy for Performing Geologic Mapping

Most 7.5-minute quadrangles in the I-81 corridor have geologic coverage that falls into one of the following categories: published mapping at 1:24,000 scale; unpublished or published mapping at a scale between 1:50,000 and 1:100,000; unpublished or published mapping at a scale of 1:125,000 or 1:250,000; and no mapping at a scale of less than 1:250,000 (Figure 3). Our strategy is to compile existing blocks of published 1:24,000-scale maps and bring the level of mapping in other quadrangles up to 1:24,000-scale quality. Geologic and digital compilation will be continually expanded as new quadrangles are mapped.

Quadrangles to be mapped early in the project are those:

- where new geologic mapping is needed to address an important environmental, development or natural resource issue;
- adjacent to previously compiled geologic maps;
- where existing geologic mapping is nearly 1:24,000 quality;
- where existing geologic mapping has been completed at 1:100,000-scale.

This project requires mapping approximately 70 quadrangles. Half of these quadrangles have not previously been mapped at a scale of less than 1:250,000. The final product will involve digital compilation of these maps and approximately 60 additional quadrangles. It is anticipated that the I-81 corridor geologic mapping project could be completed in approximately 12 years with continued funding. For 2008-2009, the project will consist of the two separate sub-projects outlined below:

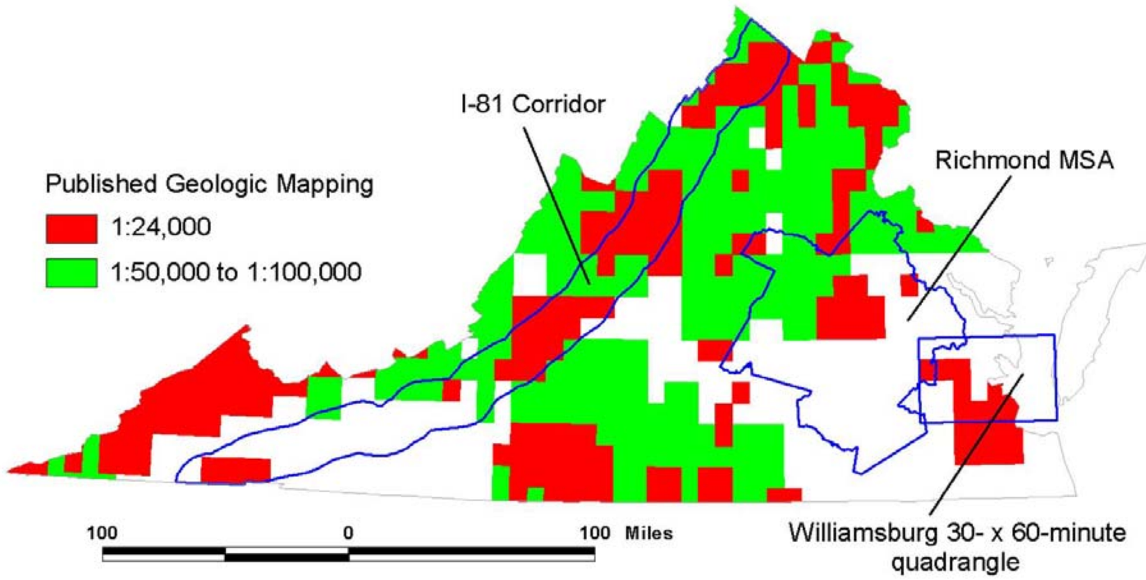

Figure 3. Published geologic map coverage in Virginia. Other areas rely upon 1:125,000- and 1:250,000-scale maps of the Coastal Plain and Appalachian Valley or the 1:500,000-scale state map.

1. New Geologic Mapping (4.25 quadrangles)

New 1:24,000-scale mapping of the, Broadford (½), Cedar Springs (½), Collierstown, Cornwall, Elliston (½), Montebello (½), and Stanley (¼) quadrangles is proposed (Figure 4). All of these quadrangles are entirely or substantially within the I-81 corridor.

As part of the mapping program, samples that are representative of significant map units will be collected. One portion of these samples will be submitted for whole rock analysis. A second portion will be used to make thin sections. A third portion will be placed into our rock repository. Whole rock analyses will include major, minor, trace and rare earth elements. The analytical results will be used to correlate rock types and identify potential mineral resources, including high calcium limestone. The results will be compiled into a database that is available to the public. One anticipated use is to identify the background concentrations of metals such as arsenic, barium, cadmium, chromium, lead, and mercury that are routinely detected in soil and groundwater during environmental investigations. Physical testing of potential aggregate resources may also be completed.

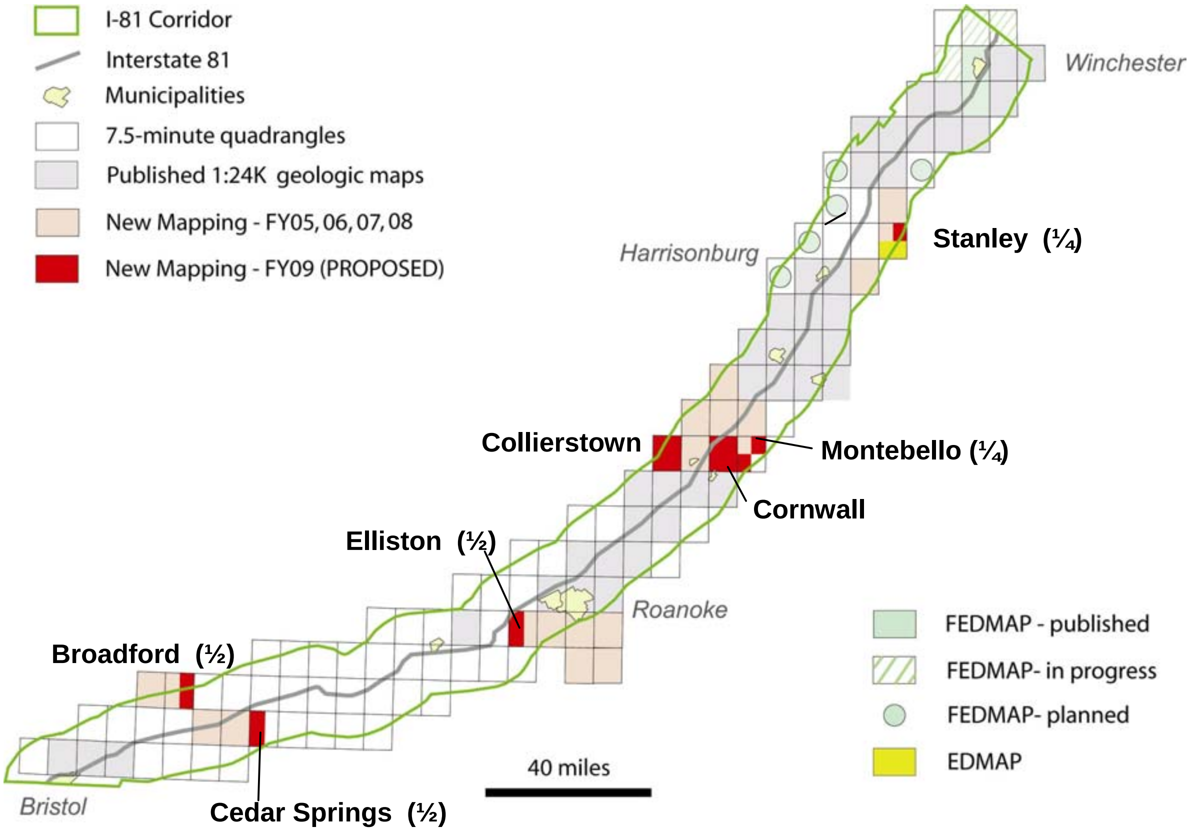

Figure 4. 7.5-minute quadrangles proposed for new geologic mapping within the I-81 Corridor project. FY= Virginia fiscal year (July 1 – June 30).

2. Geologic Compilation of Existing Maps (4 quadrangles)

This project will build upon our 2003 through 2008 STATEMAP geologic compilation, consisting of 32 7.5-minute quadrangles. This year we will add the following four quadrangles: Atkins, Elkton West, Goshen, and Vesuvius (Figure 5). All of the quadrangles are wholly or substantially within the I-81 Corridor. The average cost of the proposed digital compilation is $9,318 per quadrangle. The average amount of federal funds requested per quadrangle is $4,410.

Geologic mapping of these quadrangles has been completed during the past three years. As a result, significant internal field checking of these quadrangles will not be required. Field checking along boundaries with other existing quadrangles may be required.

The GIS files for these quadrangles will be created by digitizing or importing and editing the geologic features from the original maps as points, lines and polygons, attributing these features and incorporating any changes and new data resulting from field checking. Metadata and printable maps will be created based on the updated geologic information.

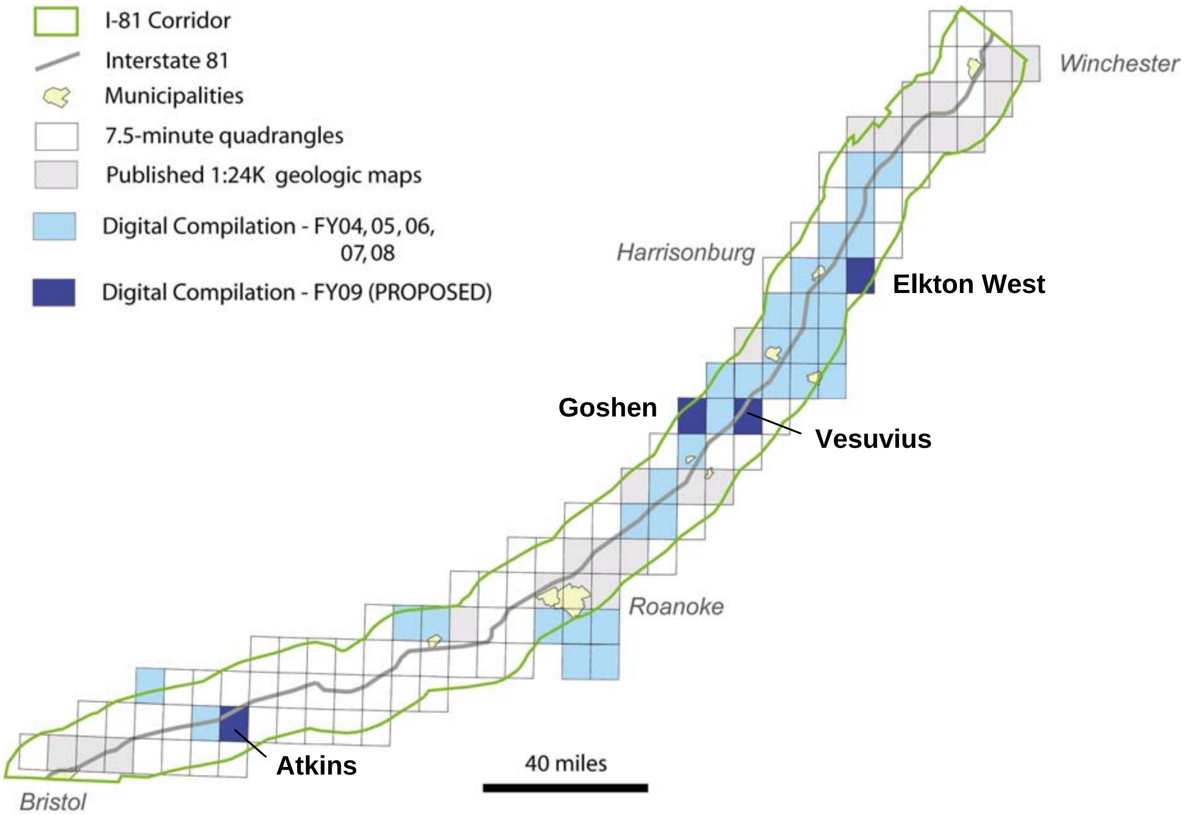

Figure 5. 7.5-minute quadrangles proposed for digital geologic compilation within the I-81 Corridor project. FY= Virginia fiscal year (July 1 – June 30).

Preliminary Results and Previous Work

Between 2004 and 2007, new geologic mapping of 13 quadrangles has been completed for the I-81 Corridor project (Augusta Springs, Atkins (½), Bent Mountain, Boones Mill, Brownsburg, Elkton West (½), Garden City, Grottoes (½, surficial), Hardy, Hamburg, Lexington, Marion, Redwood, Saltville, and Vesuvius). Our current STATEMAP project involves mapping the Atkins (½), Broadford (½), Elkton West (½), Elliston (½), Montebello (¼), and Stanley (¼) quadrangles.

Our 2003-2007 digital compilation projects included a total of 26 1:24,000 geologic maps along the Interstate 81 corridor (Figure 5). Newly acquired and original field data have also been incorporated into the compilation. Approximately eighteen months of fieldwork have been completed to resolve map boundary discrepancies, structural complexities, and to provide new data upon which to base cross sections. Our current STATEMAP digital compilation for the I-81 Corridor project includes the revision and compilation of the Augusta Springs, Bent Mountain, Conicville, Edinburg, Redwood, and Saltville quadrangles (Figure 5).

New mapping and targeted remapping for this project is helping to refine the stratigraphy and structure of the Valley and Ridge province and adjacent Blue Ridge and Inner Piedmont. Field checking in the Martinsburg formation in the Fort Defiance, Staunton, Stuarts Draft, and Waynesboro West quadrangles in 2003-2004 provided evidence for multiple periods of deformation within the Martinsburg Formation (Duncan and Others, 2004). Field checking along the Blue Ridge front in the Crimora, Waynesboro East and Waynesboro West quadrangles in 2004-2005, supported by seismic profiles made available since the original maps were published, provided evidence for the existence of a "Blue Ridge" fault separating Chilhowie Group rocks from those of the Rome Formation (Williams and others, 2006). This is a change from the original maps, which show an intact stratigraphic sequence, and is consistent with recent interpretations further south in Virginia and North Carolina. Mapping in the Boones Mill, Garden City and Hardy quadrangles in 2004-2005, supported by geochemical analyses, has helped to establish genetic relationships among deformed plutonic and volcanic rocks of the Blue Ridge and inner Piedmont (Henika, 2006). Mapping in the Marion and Atkins Quadrangles in 2005-2007 identified areas that contain Ordovician-age limestones in addition to previously recognized Cambrian-age Honaker and Nolichucky Formations. This resulted in redefining the Hungry Mother Creek and Greenwood faults as a remnant of a thrust that overlies the Saltville sheet, rather than imbricate thrusts within the Saltville sheet. Mapping in the Augusta Springs quadrangle in 2006-2007 has confirmed the existence of a significant structure, the Little North Mountain fault, which appears to tie into the North Mountain fault. Ongoing mapping in the Elkton West quadrangle confirms the presence of a significant backthrust within the Massanutten synclinorium (Heller and Others, 2007). Geochemical analyses completed to support the project provide useful information on natural concentrations of potentially harmful elements in and acid forming potential of shales in the Shenandoah Valley (Coiner and others, 2007).

Previous Work

1:24,000-scale maps of portions of the Stanley quadrangle are available (King, 1950; Sarros, 1995). The Elliston quadrangle has previously been mapped at 1:100,000-scale (DMR, Unpublished data). The Collierstown and Cornwall quadrangles have been mapped at 1:50,000-Scale (Wilkes, in preparation). The Montebello quadrangle has been mapped at 1:62,500-scale (Werner, 1966). A portion of the Montebello quadrangle in the Irish Creek tin district has been the focus of detailed mapping and investigation (e.g. Koschmann and others, 1942; Hudson, 1981). A portion of the Broadford quadrangle was mapped at 1:12,000-Scale by Ross (1965).

Deliverable Geologic Maps

The deliverables for this project will be:

1. Geologic map and cross-section of half of the Broadford quadrangle;
2. Geologic map and cross-section of half of the Cedar Springs quadrangle;
3. Geologic map and cross-section of the Collierstown quadrangle;
4. Geologic map and cross-section of the Cornwall quadrangle;
5. Geologic map and cross-section of half of the Elliston quadrangle;
6. Geologic map and cross-section of half of the Montebello quadrangle;
7. Geologic map and cross-section of quarter of the Stanley quadrangle;
8. Digitally compiled geology as GIS files of the following four 1:24,000 quads: Atkins, Elkton West, Goshen, and Vesuvius (paper copies of each quadrangle that is part of the compilation will also be provided).

RICHMOND METROPOLITAN STATISTICAL AREA PROJECT

Introduction

DMR proposes to continue a multi-year effort to complete 1:24,000-scale geologic mapping and digital compilation of existing geologic maps in a portion of a 16-county area that has been designated by the U.S. Office of Management and Budget as the Richmond Metropolitan Statistical Area (MSA). According to the U.S. Census Bureau website, "the general concept of a metropolitan or micropolitan statistical area is that of a core area containing a substantial population nucleus, together with adjacent communities having a high degree of social and economic integration with that core." DMR and the GMAC have targeted the Richmond MSA for investigation because it is a recognized jurisdiction that encompasses the area of future growth around Richmond.

The Richmond MSA straddles the Piedmont and Coastal Plain provinces. It is situated at the intersection of three major interstates, I-95, I-64, and I-85 (Figure 1). This area is home to approximately one in seven of Virginia's citizens, and houses nearly every type of business and industry. Outside of developing areas, agriculture is a stable to growing part of the economy, with approximately 4,300 farms on nearly one million acres (U.S. Department of Agriculture, 1997 and 2002). This area encompasses all or a portion of six regional planning districts.

DMR has ranked the 95 unpublished 7.5-minute quadrangles that are substantially within the Richmond MSA either a low or high priority. This ranking is based upon societal needs identified by the planning districts or other government agencies and the potential for mineral resources or geologic hazards. Quadrangles that are assigned a high priority ranking meet one or more of the following criteria:

- Significant change in land use anticipated;
- High potential for mineral resources;
- Known geologic hazards exist;
- Population center or highly developed area;
- Along an Interstate.

The goal of this project is to complete 1:24,000-scale geologic mapping of all quadrangles in the MSA that are identified as high priority (Figure 6). An ultimate goal is to use this data in combination with existing data on the low priority quadrangles to create a 1:100,000-scale geologic map of the entire MSA. Intermediate products for this study will be 1:24,000-scale geologic maps of single or multiple quadrangles, to be published in paper or digital form, and a series of open-file reports on CD that contain files for the current extent of the geologic compilation.

Location and Geologic Setting

The Richmond MSA encompasses 16 counties in the Piedmont and Coastal Plain of Southeast Virginia. The cities of Richmond, Petersburg, Colonial Heights, and Hopewell are located along interstates I-95, I-64, and I-85. Several major U.S. Highways connect these cities with smaller communities both inside and outside of the MSA. The region contains significant portions of three river basins. From north to south they are the York, James, and Chowan. The lower portions of the York and James rivers flow through the area and into the Chesapeake Bay. Several smaller rivers form the headwaters of the Chowan River, which begins in North Carolina and becomes part of the Albemarle/Pamlico-River Basin. The Chesapeake Bay and the lower reaches of the Albemarle/Pamlico-River Basin represent the largest and second largest estuarine systems in the United States, respectively.

The western half of the Richmond MSA is located in the Piedmont physiographic province. Crystalline rocks in the Piedmont portion of the MSA may be assigned to three separate terranes. From west to east they are the Chopawamsic terrane, the Goochland terrane, and the Southeastern Piedmont terrane. The Chopawamsic terrane contains metavolcanic, metaplutonic and metasedimentary rocks of similar age that are believed to have formed in an early to middle Paleozoic-age volcanic arc (Coler and others, 2000). The Goochland terrane is composed of multiply deformed igneous rocks and metamorphic rocks of uncertain affinity. At least a portion of the Goochland terrane is Mesoproterozoic in age. The Goochland terrane is separated from the Chopawamsic terrane by the Spotsylvania shear zone and from the Southeastern Piedmont terrane by the Hylas shear zone (Spears and others, 2004). The Southeastern Piedmont terrane contains a variety of metamorphic rocks, some of which appear to have volcanic protoliths. The late Paleozoic-age Petersburg Granite intrudes a substantial portion of the Southeastern Piedmont terrane in the project area. Another portion is unconformably overlain by Mesozoic-age sedimentary rocks of the Farmville, Richmond, and Taylorsville basins, which were deposited in a series of half-grabens. All three of these basins have had historic coal production and oil and gas exploration.

Much of the eastern half of the Richmond MSA lies within the Fall Zone. In this complex zone, Coastal Plain sediments overlie rocks of the eastern Piedmont. Both sediment and rocks are exposed and mappable. The age of sediments ranges from Cretaceous through Holocene. Estuarine and fluvial sediments of Miocene-Pliocene age are found capping the higher elevations and become thinner to the west, extending at least 20 miles west of the Fall Line (boundary at land surface between the Piedmont and Coastal Plain provinces) at Richmond.

Purpose and Justification

Water Resource Location

The City of Richmond and nearby counties of Henrico and Chesterfield in the Richmond MSA obtain their water supplies from surface sources, including the James River. Most other public and private water supplies in the MSA are groundwater-based. Well yields and water quality vary depending upon rock type, location, and depth. Shallow wells in the Coastal Plain may be vulnerable to surface contamination. In fractured crystalline rock aquifers, well yields are unpredictable, although supplies are typically adequate for residential use. Higher yield supplies for industries and municipalities are more difficult to locate. Detailed geologic mapping will provide useful information to municipalities, businesses, and industries when siting reservoirs and wells.

Economic Product Development

The Richmond Metropolitan Statistical Area (MSA) currently contains over 50 active mine and quarry operations, which produce economically significant quantities of crushed stone, clay, sand, gravel, and several industrial minerals. The crushed stone, clay, sand, and gravel resources provide local sources for high-demand construction materials. Industrial minerals such as aplite, vermiculite, and fuller's earth are exported from the Richmond area, providing business income and local jobs. Titanium and zircon are currently being produced from a nationally significant heavy mineral mine in the southern part of the MSA.

Past mineral production in the Richmond MSA includes many commodities not currently being produced, but which may have potential for redevelopment in the future. Coal was produced locally for over two hundred years; while it's not likely that coal mining will return to Richmond, deep coal deposits have been explored in recent years for coal bed methane. Gold, sulfide minerals, and mica were produced in the past and may still be present in significant quantities. Improvements in technology or changes in demand may make some of these commodities economically viable in the future. Building and dimension stone played a significant role in the growth and development of the City of Richmond until the 1940's. Detailed geologic maps will be critical for the evaluation and development of these resources.

Geologic Hazard Identification

Known geologic hazards in the Richmond MSA include acidic soils, shrink-swell soils, subsidence in the vicinity of abandoned underground mines, flooding, slope stability, and unsafe levels of radon and other potentially hazardous naturally occurring elements in soil and groundwater.

Surface collapses in the vicinity of historic coal mines in the Richmond basin have been a significant problem in recent years, because of residential and commercial development in former coal mining areas. Since most of these mines were abandoned in the 1800's, their exact locations and extents are often unknown. Acidic soils associated with the Eastover Formation (Miocene lower Chesapeake Group) are widespread in the eastern portion of the Richmond MSA. Water discharging from these soils can have a pH of 2 or 3. This can contribute to habitat degradation in streams and the premature failure of concrete and metal structures. The remnants of tropical depression Gaston in 2004 caused severe flooding and numerous landslides in downtown Richmond and vicinity. Understanding the geology of this area will help reconstruction and prevent future landslides.

Natural Resource Protection

Developmental pressures within the Richmond MSA are causing changes in land use. During development, open space is converted to industrial, commercial, and residential use. These changes are certain to have both positive and negative effects on the region's natural resources. In many cases, the geology can play an important role in the nature and extent of these impacts. Detailed geologic maps will provide useful information to land use planners, natural resource caretakers, and environmental consultants who work in the MSA. The Petersburg and Richmond National Battlefield sites are located in the Richmond MSA. The National Park Service has expressed interest in geologic mapping of these properties and surrounding areas to support park management.

Water contamination is a significant problem in many parts of Richmond MSA. Water quality in the region is impacted by a number of pollution sources, including contaminated water run off and excessive sedimentation (Virginia Department of Environmental Quality, 2003). Non-point and point source pollution in developing areas also contributes fertilizers, pesticides, petroleum products, solvents, and other chemicals to streams and aquifers. Development often results in greater areas of impervious surfaces, resulting in increased surface overland flow into streams. 62 percent and 51 percent of monitored streams and rivers in the York and James River Basins, respectively, are threatened, not fully supporting, or not supporting aquatic life (Virginia Department of Environmental Quality, 2003). These rivers affect water quality in the Chesapeake Bay. Monitoring suggests that 93 percent of the Chesapeake Bay is threatened, not fully supporting, or not supporting aquatic life.

Waste Disposal Facility Siting

As development in the region continues, additional solid and liquid waste disposal facilities will need to be constructed. These include municipal landfills, wastewater treatment plants, and land application sites. Detailed geologic maps will provide useful information to the decision makers who site and regulate these facilities.

Roads and Infrastructure Development

Several major highway construction projects are underway or are being planned for the future, including the expansion and realignment of U.S. Highway 460 and the widening of I-64 east of Richmond. Detailed geologic maps will provide useful information to the Virginia Department of Transportation, municipal and private utilities, and private and public land developers.

Science Issues

The Richmond MSA straddles the Piedmont and Coastal Plain provinces. As a result, the scientific problems addressed by our research fall into two categories. A top priority in the Piedmont is deciphering the potentially complex metamorphic history of the Petersburg Granite. Although traditionally portrayed as a single, homogenous pluton (e.g., Calver and others, 1963), our detailed mapping in the Richmond area demonstrates that the granite can be subdivided into four phases, following the earlier work of Bobyarchick (1978), and challenges the relevance of a single geochronometric date for the entire outcrop belt (i.e., Wright and others, 1975). Foliations occur in all phases of the Petersburg Granite. Bobyarchick (1978) suggests a generally igneous origin for these foliations, but notes recrystallization and deformation in quartz (undulatory extinction and early stages of subgrain development). We also observe incipient subgrain development to strong quartz recrystallization in many samples, as well as multiple foliations in some outcrops, which lead us to speculate that much of the Petersburg Granite has been metamorphically overprinted.

The relationship of the Petersburg Granite to a) metavolcaniclastic rocks of the Southeastern Piedmont terrane, and b) rocks of the Goochland terrane west of the Hylas fault zone is not well understood. Regional reconnaissance mapping (i.e., Mixon and others, 1989; Virginia Division of Mineral Resources, 1993) shows the Petersburg Granite and multiply metamorphosed volcaniclastic rocks of the Southeastern Piedmont to be in fault contact, but significant metamorphism within the granite may lead to other contact interpretations. Likewise, granites of similar composition, texture, geochemistry and presumed age as the Petersburg Granite crop out in the Goochland terrane, including the Fine Creek Mills (Poland, 1976) and Flat Rock (Reilly, 1980). These granites, if they are truly coeval with the Petersburg, effectively link the Southeastern Piedmont with the Goochland terrane prior to the formation of the Hylas fault zone during the Alleghanian. However, potential metamorphic ties between the Petersburg Granite and metavolcanic rocks farther south may challenge accepted Alleghanian accretionary tectonic models.

In the Coastal Plain, we have now been able to extend the Bacons Castle Formation (Coch, 1965) and Chesapeake Group (Ward and Blackwelder, 1980) from the outer Coastal Plain subprovince, following Mixon and others (1989), to the Inner Coastal Plain in the Richmond area at 1:24,000-scale. Researchers can now begin to expand the Chesapeake Group into recognized formal units, based primarily on detailed paleontologic and stratigraphic studies. In addition, our detailed maps and borehole databases in the Coastal Plain are allowing us to construct derivative isopach maps, which will provide paleographic interpretations of sea level fluctuations from the Cretaceous to the present in the Richmond area.

Strategy for Performing Geologic Mapping

Most 7.5-minute quadrangles in the Richmond MSA have geologic coverage that falls into one of three categories: published mapping at 1:24,000 scale; unpublished or published mapping at a scale between 1:24,000 and 1:250,000; and no mapping at a scale of less than 1:250,000 (Figure 3). Our strategy is to compile existing blocks of published 1:24,000-scale maps and bring the level of mapping in high priority quadrangles up to 1:24,000 quality. Geologic compilation will be continually expanded as new quadrangles are mapped.

Quadrangles to be mapped early in the project are those:

- where new geologic mapping is needed to address an important environmental, development or natural resource issue;
- adjacent to previously compiled geologic maps;
- where existing geologic mapping is nearly 1:24,000 quality.

This project will require mapping approximately 45 quadrangles (Figure 6). Unpublished data exist for many of these quadrangles, but only seven are covered by published mapping at a scale of greater than 1:250,000. The final product will involve the compilation of these maps and 13 previously published quadrangles. It is anticipated that the Richmond MSA geologic mapping project could be completed in approximately 13 years with adequate staff and funding. For 2007-2008, we propose the project outlined below:

New Geologic Mapping (3 quadrangles)

1:24,000-scale mapping of the Dutch Gap, Glen Allen, and Providence Forge quadrangles is proposed (Figure 6). The Dutch Gap and Glen Allen quadrangles are adjacent to our area of recent mapping and compilation. The Providence Forge quadrangle is adjacent to the Walkers quadrangle on the Williamsburg 30- x 60-minute quadrangle. All three quadrangles are ranked by DMR as high priority because they contain highly developed and developing areas.

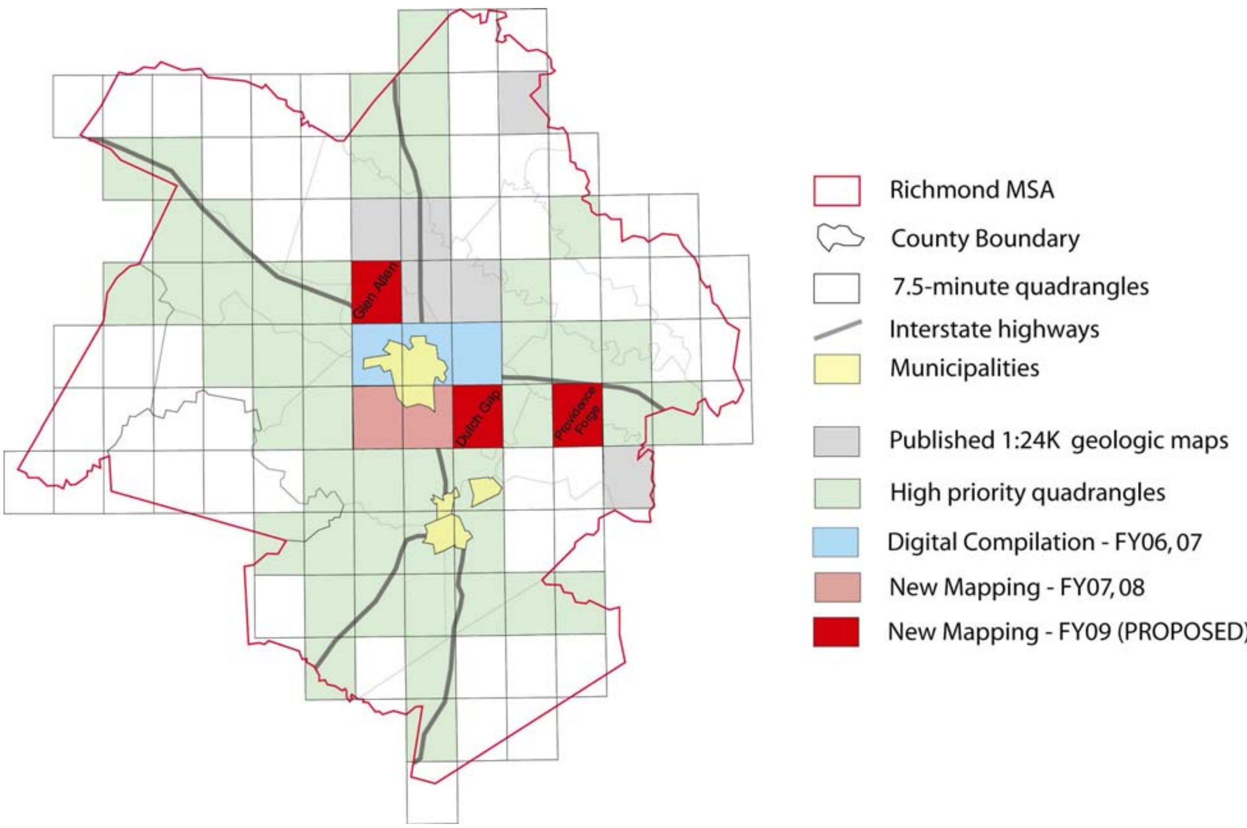

Figure 6. 7.5-minute quadrangles proposed for new mapping within the Richmond MSA project area. FY= Virginia fiscal year (July 1 – June 30).

As part of the mapping program, samples that are typical of significant map units will be collected. A portion of these samples will be submitted for whole rock analysis. A second portion of consolidated rocks will be used to make thin sections. A third portion of consolidated rocks will be placed into our rock repository. Whole rock analyses will include major, minor, trace, and rare earth elements. The analytical results will be used to correlate rock types and identify potential mineral resources. The results will be compiled into a database that is available to the public. One anticipated use is to identify the background concentrations of metals such as arsenic, barium, cadmium, chromium, lead, and mercury that are routinely detected in soil and groundwater during environmental investigations.

The Glen Allen quadrangle was published in 1981 (Goodwin, 1981). Significant development has occurred in this area during the intervening time, creating new exposures.

Based on our experience in the Richmond, Bon Air, and Seven Pines quadrangle, we anticipate that significant fieldwork will be needed to make the stratigraphy and data density for the Glen Allen quadrangle consistent with our ongoing geologic compilation. In areas where crystalline rocks are exposed, an emphasis will be placed on measuring the orientations of joints and filled fractures, which are lacking on the original map. Targeted remapping of problem areas, the addition of structural data and the updating of stratigraphic nomenclature will also be performed.

Preliminary Results and Previous Work

Preliminary Results

We are in our third year of compiling new and existing geologic maps in the Richmond MSA. In our first two years, we significantly updated and re-mapped previously published geologic maps of the Richmond, Bon Air, and Seven Pines 7.5-minute quadrangles and began new mapping on the Chesterfield and Drewry's Bluff 7.5-minute quadrangles. This year we are completing the Chesterfield and Drewry's Bluff quadrangles. This work has significantly increased our understanding of inner Coastal Plain and Southeastern Piedmont stratigraphy, structure, and geomorphic evolution, and highlighted several geologic issues of societal importance:

Petersburg Granite and potential Radon Gas emissions

Previous geologic maps (Daniels and others, 1974; Goodwin, 1980, 1981) grossly subdivided the Mississippian Petersburg Granite into two units in this area: uniform textured granite, and porphyritic granodiorite. We are now accurately delineating four phases of Petersburg Granite intrusion: early phases consisting of layered granite gneiss and well-foliated granite, a fine- to coarse-grained subidiomorphic middle phase, and a late phase of coarse porphyritic granite in map-scale screens and discrete zones. Within these phases, we are also recognizing map-scale xenoliths of biotite gneiss and schist, and mafic and altered ultramafic rocks. A research goal in the coming year is to gather existing radon data in the map area and look for correlations with the four granite phases; if significant associations are found, our new maps may be useful for outlining areas with greater potential for radon problems.

Economic Earth Material and Mineral Resources

Definition and nomenclature of Coastal Plain stratigraphy has significantly increased in the years since publication of the original quadrangles in this area. For instance, we now recognize that Pliocene Yorktown Formation (upper Chesapeake Group) and Pliocene-Pleistocene Bacons Castle Formation lithologies extend westward into the inner Coastal Plain (e.g., Mixon and others, 1989). Our new mapping demonstrates that sand and gravel of the Bacons Castle Formation underlies vast areas of the Richmond and Seven Pines quadrangles between the Chickahominy and James Rivers, and is a virtually untouched source of aggregate in this increasingly urbanized region. Additionally, we have recognized internal stratigraphy within the near-shore facies of the Yorktown Formation in the Richmond area. South of Petersburg, similar Yorktown lithofacies hold the largest deposits of heavy minerals in the eastern US. Continued detailed mapping in the Richmond area may reveal additional reserves.

Relationship between surfical deposits and Cenozoic faults, and Paleo-seismicity

West of Richmond on the Bon Air quadrangle, new mapping has revealed a heretofore-unrecognized surficial unit consisting of rounded pebbles, cobbles, and boulders within a matrix of quartz and feldspar clayey sand (Carter and others, 2006). Clasts are unsorted, matrix supported, and consist of quartz, quartzite, and granite. Mapping suggests that the unit represents Tertiary to Quaternary colluvium, shed down-slope from Miocene and Pliocene upland gravel terraces. Surprisingly, our new work also suggests a relationship between the colluvium and silicified cataclasite zones in the underlying granite. Although traditional interpretation dictates silicified cataclasites are Mesozoic in age, several key exposures hint that the colluvium is offset by, or deposited down-dip of apparently reactivated silicified cataclasite zones. Likewise, reactivated silicified cataclasites may have also controlled deposition of a heretofore-unmapped fossiliferous marine clayey to silty fine sand unit that locally underlies Miocene upland gravel terraces south of the James River. This unit may be equivalent to the Miocene Eastover Formation that crops out to the east on the Richmond and Seven Pines quadrangles; if so, there is an approximately 150 ft elevation difference between the outcrop belts. Continued mapping (coupled with paleontologic, geochemical, and petrographic analyses) should a) further constrain the age of the colluvial deposits and the marine clayey sand unit beneath the upland gravels, and b) determine the role of Cenozoic faulting and paleoseismicity recurrence.

Previous Work

The Glen Allen map has previously been published at 1:24,000-scale (Goodwin, 1981). Although we anticipate being able to use the majority of the contacts on this map, we have determined that the amount of effort required to make the Glen Allen quadrangle consistent with our ongoing compilation will be nearly equivalent to remapping. For the Dutch Gap and Providence Forge quadrangles, we have field data collected for the completion of the 1:250,000-scale map of the Virginia’s Coastal Plain (Mixon and others, 1989) or the 1:500,000-scale Geologic Map of Virginia (VDMR, 1993)

Deliverable Geologic Maps

The deliverables for this project will be:

1. Geologic map and cross-section of the Dutch Gap quadrangle;
2. Geologic map and cross-section of the Glen Allen quadrangle;
3. Geologic map and cross-section of the Providence Forge quadrangle.

WILLIAMSBURG 30 x 60-MINUTE QUADRANGLE PROJECT

Introduction

DMR proposes to continue its effort to complete geologic mapping and digital compilation in the Williamsburg 30- x 60-minute quadrangle (Figure 1). There are approximately 4.5 7.5-minute quadrangles (and small parts of two quadrangles on the Eastern Shore) that have not been mapped in detail (Figure 7). Six 7.5-minute quadrangles in the Williamsburg sheet were mapped between 2000 and 2006 with STATEMAP funding. Mapping the Walkers 7.5-minute quadrangle will complete the northern half of the 30- x 60-minute quadrangle. The Walkers quadrangle is along I-64, and is experiencing rapid development.

DMR relies heavily upon the use of its auger drilling rig for geologic mapping in the coastal plain. Although exposed map units may appear simplistic in some coastal areas, a refined delineation of the subsurface framework is critical to understanding the shallow aquifers and identification of sand/aggregate resources. STATEMAP funding will support assistance with mapping, drilling, sample analysis, and GIS compilation.

The final product for this project will be a 1:100,000-scale digital compilation of the entire Williamsburg sheet. We anticipate that it will take approximately two years to finish the project.

Location and Geological Setting

The Williamsburg 30- x 60-minute quadrangle lies completely within the tidewater region of Virginia (Figure 1). I-64 passes diagonally through the map area and is the major corridor for travel, commerce, and development between Richmond and the Virginia Beach–Norfolk–Newport News area. The trace of the interstate here defines the southern part of the “Golden Crescent” (an area of high population and development) that continues from Richmond to Washington DC. Other prominent geographic features are the York and James rivers, two major estuaries that are tributaries to the Chesapeake Bay. The eastern third of the Williamsburg sheet encompasses both shorelines of the lower Chesapeake Bay.

The region is home to major tourist attractions such as Colonial Williamsburg, Busch Gardens, Colonial National Historical Park, and Jamestown Settlement. It also contains industries such as Newport News Shipyard, coal and shipping terminals. Military bases include Fort Monroe, Fort Eustis, Yorktown Coast Guard Center, Langley Air Force Base, Yorktown Naval Weapons Station, and Camp Peary. This development is sometimes in conflict with the seafood industry centered in the lower bay and tributary estuaries.

The Williamsburg map area is entirely within the Coastal Plain province. Map units exposed above sea level consist predominately of estuarine, nearshore marine, and marine unconsolidated sediments of Pliocene and Pleistocene age. There is limited exposure of Miocene marine sediments in the project area. There is a substantial link between the morphology (scarps and flats) and Pleistocene stratigraphy because of world-wide sea-level changes during repeated glacial activity.

Below sea level, early Tertiary and Cretaceous sediments overlie basement rocks. Strata dip as a thickening wedge seaward. Depth to basement ranges from approximately

800 feet in the west part of the map area, 2,100 feet at Newport News to possibly 7,000 feet in the east at Cape Charles. However, the center of the Chesapeake Bay Impact Crater (33My) is located below Cape Charles, with a zone of fractured and faulted basement rocks extending more than 25,000 feet below sea level. The crater has affected basement and overlying Cretaceous through Eocene age sediments out to a diameter of 56 miles (Powars, 2000). Faults believed to be as young as Pliocene are associated with the outer rim go through the study area in the Gloucester, Mathews, Newport News, and Hampton quadrangles.

Purpose and Justification

Water Resource Location

Water supply in the project area comes from surface impoundments and wells. A desalinization plant is under construction for James City County. The city of Newport News has developed several reservoirs in the map area and is in the permit process for an additional reservoir in King William County. The impounded Chickahominy River and the Diascond Reservoir lie within the Walkers 7.5-minute quadrangle (proposed to be mapped in 2006-2007). Newport News and Gloucester have recently begun pumping and desalinizing brackish groundwater to increase their water supply.

Economic Product Development

Sand and gravel resources in the Williamsburg area are currently being lost to housing development. Most of the richest deposits in the coastal plain are found in the fluvial parts of the Pleistocene terraces, adjacent to major rivers (estuaries). Using DMR's auger drill rig greatly enhances the capability of locating potential aggregate resources. Fossil shell beds have been used as a source of lime (calcium carbonate) and may have a future use as a substrate for reseeding oyster beds. Our mapping has also suggested the presence of heavy mineral deposits in this region.

Geologic Hazard Identification

Coastal flooding, elevated radon concentrations, minor earthquakes, landslides, sinkholes, shrink-swell clays, and acidic soils are known or potential geologic hazards in the project area.

Natural Resource Protection

Development pressures within the project area are causing changes in land use. During development, open space is converted to industrial, commercial, and residential use. These changes are certain to have both positive and negative effects on the region's natural resources. In many cases, the geology can play an important role in the nature and extent of these impacts. Detailed geologic maps will provide useful information to land use planners, natural resource caretakers, and environmental consultants who work in the area. We provide regular updates of geologic mapping to the Colonial National Historical Park for management of natural resources at historic sites (Green Springs Plantation, Jamestown Island fort rediscovery).

Water contamination is a significant problem in some parts of the project area, which encompasses a lower portion of the Chesapeake Bay. Please refer to this section of the

Richmond MSA project proposal for additional information about the York and James River Basins.

Roads and Infrastructure Development

Several major highway construction projects are underway or are being planned in the future, including the expansion and realignment of U.S. Highway 460. Detailed geologic maps will provide useful information to the Virginia Department of Transportation, municipal and private utilities, and private and public land developers.

Strategy for Performing Geologic Mapping

In order to compile at 1:100,000-scale, mapping will be done at 1:50,000-scale or better and 1:24,000-scale where necessary. At least 25 auger borings will be made in the quadrangle with subsurface information entered into a Microsoft Access database. Geologic contacts and point data will be compiled in a GIS. Rick Berquist will be mapping the quadrangle with assistance from an employee to-be-hired.

Science Issues

The first permanent English colony in the New World began at Jamestown in 1607, as did exploration for natural resources. Gold was not discovered in Virginia until the early 1700's, but the making of iron and the search for ore resulted in the first (commercial) blast furnace in America in 1619. Our local geologic mapping allows us to assist, collaborate with and advise archaeological researchers and interpreters with the Association for the Preservation of Virginia Antiquities (APVA), the National Park Service, Jamestown Settlement, and the Colonial Williamsburg Foundation with potential historic ore locations and identification and source of lithic materials.

Although Virginia was not glaciated in the Pleistocene, the effects of those global sea-level changes are profoundly linked to coastal plain stratigraphy. The tidewater area of Virginia is undergoing eustatic (and in some places more rapid) sea-level rise. With increased geologic mapping, the "past may become the key to the present" for understanding and prediction of potential events associated with local sea-level rise.

The Pliocene in Virginia was quite active; specifically, there was reverse faulting in the Fall Zone, massive sediment deposition resulting in the widespread Yorktown and Bacons Castle formations, formation of widespread sand and gravel resources, and the concentration of heavy minerals. As our mapping closes between Richmond and Williamsburg, the details of stratigraphic relations between nearshore and marine Yorktown sediments, and fluvial to estuarine (tidal prism) sediments of the Bacons Castle Formation, are expected to become more clear.

New Geologic Mapping (2/3 quadrangle)

For 2007-2008, we propose complete mapping the Surry 7.5-minute quadrangle, south of the James River (Figure 7). The Surry quadrangle encompasses a largely rural population, but development, particularly along shorelines has rapidly increased over the past few years. Cliffs that expose excellent and historic outcrops along the James River are being regraded, planted and covered with riprap with consequent loss to future stratigraphic and paleontologic research. The Surry area hosts the prominent Surry Scarp, as well as the problematic relationship between the informal "Moorings unit" and Windsor Formation. There is likely no better place to resolve this stratigraphic problem than here with subsequent mapping to the south and west.

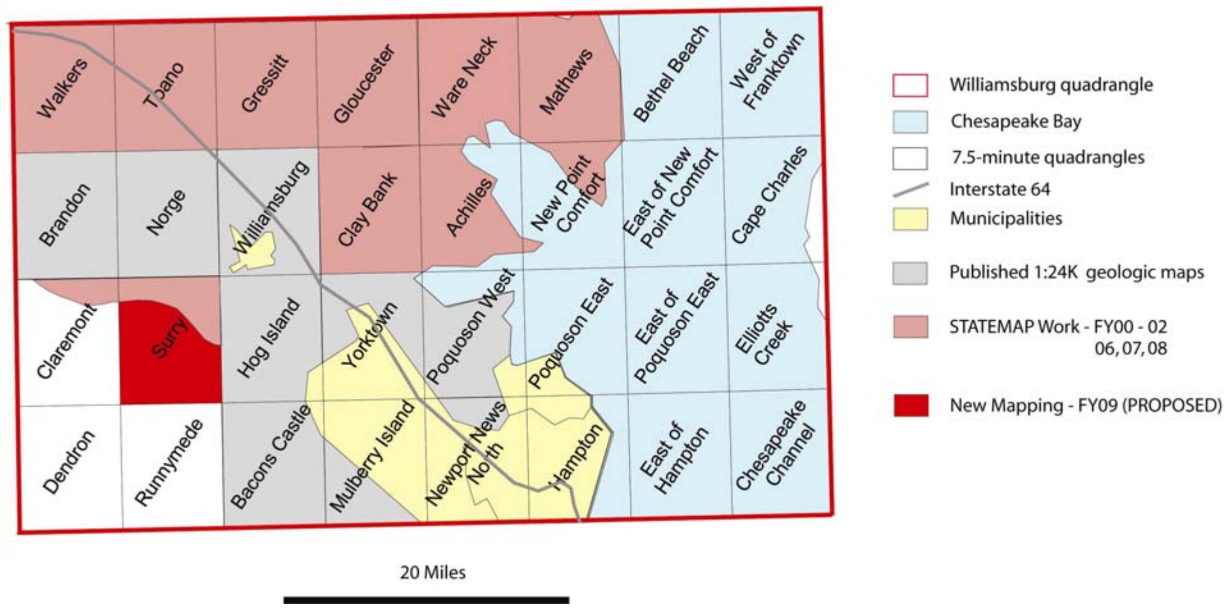

Figure 7. 7.5-minute quadrangle proposed for new mapping within the Williamsburg 30- x 60-minute quadrangle project area. FY= Virginia fiscal year (July 1 – June 30).

Preliminary Results and Previous Work

Preliminary Results

The mapping of Gloucester quadrangle and portions of the Surry and Claremont quadrangles was completed in June 2007 under our previous STATEMAP grant. Over 50 power- and hand-auger borings were made. Additional borings have been completed in the north-central part of the area where the Sedley, Yorktown, and Eastover formations were affected by faulting associated with the outer rim of the Chesapeake Bay Impact Crater. Tertiary sediments disappear below sea level to the east of a north-south line defined by Blackwater Creek and the North River.

Geologic mapping in the Walkers quadrangle is about 20% complete. Borings to date suggest that the exposed Yorktown Formation sediments that preceded deposition of the Sedley and Bacons Castle sediments were subjected to erosion and incision with a relief of approximately 30 feet. The tidal Chickahominy River and Diascund Creek contain rare channels up to 40 feet in depth; sand, gravel, and Miocene sediments are contained within the channel depths with organic sand, organic mud and peat commonly in shallow-water channel margins.

Previous Work

All previously published maps and STATEMAP deliverables have been compiled at the original map scale (1:24,000 and 1:50,000) with a plotted map at 1:100,000-scale (Figure 7).

Deliverable Geologic Maps

The deliverable for this project will be a geologic map and cross-section of the Surry quadrangle.

REFERENCES

Bobyarchick, A.R., 1978, Reconnaissance geologic setting of the Petersburg Granite and regional framework for the Piedmont in southeastern Virginia, *in* Costain, J.K., Glover, L. III., and Sinha, A.K., Evaluation and targeting of geothermal energy resources in the southeastern United States: Virginia Polytechnic Institute and State University, Progress Report 5648-4, p. A-1 – A-27.

Butts, C., 1933, Geologic map of the Appalachian Valley of Virginia with explanatory text: Virginia Geological Survey Bulletin 42, scale 1:250,000.

Butts, C., 1940, Geology of the Appalachian Valley in Virginia: Virginia Geological Survey Bulletin 52, 568 p.

Calver, J.L., Hobbs, C.R.B., Jr., Milici, R.C., Spiker, C.T., and Wilson, J.M., 1963, Geologic map of Virginia: Virginia Department of Conservation and Economic Development, Division of Mineral Resources, scale 1:500,000.

Carter, M. W., Bleick, H.A., and Berquist, C.R., 2006, Advances in stratigraphy and structure at the Fall Zone, Richmond, Virginia: Geological Society of America Abstracts with Program, Vol. 38, No. 2.

Coch, N.K., 1965, Post-Miocene stratigraphy and morphology of the inner Coastal Plain, southeastern Virginia: U.S. Office of Naval Research, Geography Branch, Technical Report 6.

Coiner, L.V., Rodriguez, M.A., and Heller, M.J., 2007, Preliminary results of geochemical sampling and implications for environmental investigations in the southern Shenandoah Valley, Virginia: Geological Society of America Abstracts with Program, Vol. 39, No. 2., p. 31.

Coler, D., Wortman, G.L., Samson, S., Hibbard, J., Stern, R., 200, U-Pb geochronologic, ND isotopic, and geochemical evidence for the correlation of the Chopawamsic and Milton terranes, Piedmont Zone, southern Appalachian orogen: Journal of Geology, 108, p. 383-390.

Commonwealth of Virginia, 1996, Shenandoah and Potomac River basins tributary nutrient reduction strategy, 107 p.

Daniels, P.A. and Onuschak, E., Jr., 1974, Geology of the Studley, Yellow Tavern, Richmond and Seven Pines quadrangles, Virginia: Virginia Division of Mineral Resources Report of Investigation 38, 75p.

Dorman, F., 2001, Sinkholes won't swallow cars with VDOT on the job: VDOT Press Release No. 6.

Duncan, I.J., Campbell, E.V., and Williams, S.T., Multiple deformation associated with Taconic thrust sheets in the great valley of Virginia: GSA Abstracts with Programs, Vol. 36, No. 5.

Environmental Protection Agency, 2002, The state of the Chesapeake Bay: EPA 903–R–02-002, 18 p.

Goodwin, B.K., 1980, Geology of the Bon Air quadrangle, Virginia: Virginia Division of Mineral Resources, Publication 18, 1:24,000-scale map with text.

Goodwin, B.K., 1981, Geology of the Glen Allen quadrangle: Virginia Division of Mineral Resources Publication 31, 1:24,000-scale map with text.

Heller, M.J., Whitmeyer, S.J., Holland, C., Arnette, D., Carter, M.W., and Coiner, L.V., 2007, Southeast-directed backthrusting and crustal thickening in the Massanutten Synclinorium, Rockingham and Page Counties, Virginia: Geological Society of America Abstracts with Program, Vol. 39, No. 2., p. 13.

Henika, W.S., Petrology and geochemistry of metamorphosed Proterozoic igneous rocks in the Blue Ridge and western Piedmont terranes near Roanoke, Virginia: Geological Society of America Programs with Abstracts, Vol. 38, No. 2.

Hubbard, D.A., 1983, Selected karst features of the northern Valley and Ridge province: Virginia Division of Mineral Resources Publication 44, one sheet.
Hubbard, D.A., 1988, Selected karst features of the central Valley and Ridge province: Virginia Division of Mineral Resources Publication 83, one sheet.
Hubbard, D.A., 2001, Selected karst features of the Central Valley and Ridge province: Virginia Division of Mineral Resources Publication 167, one sheet.
Hudson, T.A., 1981, Geology of the Irish Creek tin district, Virginia Blue Ridge [MS Thesis]: University of Georgia, Athens, Georgia, 144 p.
King, P.B., 1950, Geology of the Elkton area: U.S. Geological Survey Professional Paper 230, 82 p.
Koschmann, A.H., Glass, J.J., and Vhay, J.S., 1942, Tin deposits of Irish Creek, Virginia: US Geological Survey Bulletin 936-K, p. 271-296.
Miller, R.L. and Wilpolt, R.H., 1944, Geology and manganese deposits of the Glade Mountain District, Virginia: Virginia Geological Survey Bulletin 61, 150 p.
Mixon, R.B., Berquist, C.R., Newell W.L., and Johnson, G.H., 1989, Geologic map and generalized cross-sections of the Coastal Plain and adjacent parts of the Piedmont Virginia: U.S. Geological Survey Map I-2033, one sheet.
Poland, F.B., 1976, Geology of the rocks along the James River between Sabot and Cedar Point, Virginia [MS Thesis]: Virginia Polytechnic Institute and State University, Blacksburg, 98 p.
Powars, D.S., 2000, The Effects of the Chesapeake Bay Impact Crater on the geologic framework and the correlation of hydrogeologic units of Southeastern Virginia, south of the James River: U.S. Geological Survey Professional Paper 1622.
Reilly, J.M., 1980, a geologic and potential field investigation of the central Virginia Piedmont [MS Thesis]: Virginia Polytechnic Institute and State University, Blacksburg, 111 p.
Ross, A.H., Jr., 1965, Geology of the Saltville-Broadford area: Virginia Polytechnic Institute, Master's Thesis.
Sarros, M.J., 1989, A Geologic Interpretation of the Stanley fault and other thrust faults in Page County, Virginia: Old Dominion University, Master's Thesis, 105 p.
Spears, D.B., Owens, B.E. and Bailey, C.M., 2004, The Goochland-Chopawamsic terrane boundary, central Virginia Piedmont, *in* Southworth, S. and Burton, W., Geology of the national capital region-field trip guidebook, U.S. Geological Survey Circular 1264, p. 223-246.
United States Department of Agriculture, 1997, Census of agriculture: http://www.nass.usda.gov/census/
United States Department of Agriculture, 2002, Census of agriculture: http://www.nass.usda.gov/census/
Virginia Department of Environmental Quality, 2003, 2002 305(b) Water Quality Assessment Report
Virginia Department of Transportation, 2002, Annual average daily travel estimates by section and route: Primary Routes and Interstates, http://virginiadot.org/
Virginia Division of Mineral Resources, 1993, Geologic map of Virginia and expanded explanation, scale 1:500,000.
Virginia Employment Commission, 2003, City/County/State population projections, http://www.vec.state.va.us/vecportal/lbrmkt/popproj.cfm
Ward, L.W., and Blackwelder, B.W., 1980, Stratigraphic revision of upper Miocene and lower Pliocene beds of the Chesapeake Group, middle Atlantic Coastal Plain: U.S. Geological Survey, Professional Paper 1346, 78 p.
Werner, 1966, Geology of the Vesuvius quadrangle, Virginia: Virginia Mineral Resources Report of Investigation 7, 53 p.

Williams, S.T., Hibbitts, H.A., and Campbell, E.V., 2006, Digital compilation of geologic maps and new structural and stratigraphic interpretations in the southern Shenandoah Valley, Virginia: GSA Abstracts with Programs, Vol. 38, No. 2, 33-9.

Wright, J.E., Sinha, A.K., and Glover, L., III., 1975, Age of zircons from the Petersburg Granite, with comments on belts of Plutons in the Piedmont: American Journal of Science, v. 275, p. 848-856.